Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 8 (2025)

Online ISSN
Print ISSN
3007-3189

http://amresearchreview.com/index.php/Journal/about

Tri-Herbal Synergistic Green Synthesis of Silver Nanoparticles: Thorough Characterization and Highly Potent Antibacterial Activity Against Multi-Drug Resistant Pathogens

Arooj Zahra
Department of chemistry, COMSATS
University Islamabad, Islamabad, Pakistan.

Muhammad Junaid
Institute of Molecular Biology and Biotechnology,
University of Lahore, Lahore, Pakistan.

Nialish Shahid
Department of Microbiology and Molecular Genetics,
Bahauddin Zakariya University Multan.

Sarosh Safdar
Institute of Molecular Biology and Biotechnology,
University of Lahore, Lahore, Pakistan

Mirza Muhammad Suleman*
Institute of Molecular Biology and Biotechnology,
University of Lahore, Lahore, Pakistan.
mirzamuhammadsuleman772@gmail.com

ABSTRACT

This antimicrobial resistance (AMR) poses a serious global health challenge, and innovative, sustainable strategies are required for the management of multidrug-resistant (MDR) pathogens. This paper investigates the green synthesis of silver nanoparticles (AgNPs) from aqueous extracts of Allium sativum (garlic), Zingiber officinale (ginger), and Nigella sativa (black cumin), leveraging the synergy of the phytochemically potent botanicals in a tri-extract model. Characterization of the as-synthesized AgNPs was through surface plasmon resonance in the UV–Visible region (420–450 nm). Dynamic light scattering (DLS) confirmed the polydisperse nature with a hydrodynamic mean size of 1044.7 nm, and zeta potential analysis (–17.9 mV) considered the colloidal stability as moderate. FTIR analysis established the presence of hydroxyl, carbonyl, and amine groups in the stabilization of the nanoparticles. SEM imaging showed the prevalent spherical morphology, and EDX proved the elemental presence of silver in addition to bioorganic residues. Antimicrobial activity of the AgNPs was concentration-dependent on Escherichia coli, Staphylococcus epidermidis, and Pseudomonas aeruginosa, with the maximum inhibition reported for E. coli and P. aeruginosa. Surprisingly, resistance in the case of Acinetobacter

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 8 (2025)

Online ISSN
Print ISSN
3007-3189

http://amresearchreview.com/index.php/Journal/about

baumannii was exhibited by it in all concentrations used in the experiment. Evaluation against contemporary literature (2020–2024) for comparison identifies the augmented antimicrobial performance as well as the novelty of the tri-extract model. The combinatorial model not only enhances the phytochemical diversity but also the functional capabilities of the nanoparticles in comparison with the single-extract model. These findings justify the development of the phytogenic AgNPs as a promising bio-based intervention for the management of the MDR infections, with the potential for antimicrobial coatings, wound healing, as well as nanopharmaceuticals.

Keywords: Silver nanoparticles, green synthesis, antimicrobial resistance, phytochemicals, Nigella sativa

Introduction

Antimicrobial resistance (AMR) has developed as one of the most consequential 21st-century global health threats, compromising the effectiveness of first-line antibiotics and hastening the spread of hard-to-treat infections [1]. Unmitigated progression of multidrug-resistant (MDR) pathogens—especially *Escherichia coli*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Acinetobacter baumannii*—has rendered many traditional treatments inefficient, resulting in heightened morbidity, extended hospital stays, and elevated healthcare expenditures [2–4]. AMR may claim up to 10 million lives a year by 2050, according to the World Health Organization, if alternative treatments are not incorporated urgently [5].

Nanotechnology in this context is a paradigm-changing strategy for next-generation antimicrobial therapy [6]. Amongst a range of nanomaterials, silver nanoparticles (AgNPs) are the most promising candidates with their broad-spectrum antimicrobial activity, high surface-area-to-volume ratio, and distinct physicochemical properties [7]. AgNPs inactivate bacteria through multiplicity of action, encompassing interference with cell membrane integrity, production of reactive oxygen species (ROS), interference with protein synthesis, and DNA interaction [8–10]. This multi-modal action not only maximizes their antimicrobial potency but also reduces the likelihood of resistance development, as opposed to conventional antibiotics, which act by interfering with a single cell-related mechanism. Nevertheless, conventional physical or chemical AgNP synthesis involves toxic reagents, energy-expensive processes, and low biocompatibility, rendering them inappropriate for biomedical applications on a mass level. By comparison, green synthesis uses naturally occurring biological agents like plant extracts, microbes, and bio-polymers as reductants, providing a cost-effective, sustainable, and environment-friendly pathway towards the production of nanoparticles. Notably, the phytochemical reductants used in green synthesis are often themselves bioactive, meaning they have the effect of synergistically enhancing the functionality and stability of the resulting nanomaterials [11,12].

Among the different sources of plants, *Zingiber officinale* (ginger), *Allium sativum* (garlic), and *Nigella sativa* (kalonji or black cumin) have gained increased interest because of their widely reported antimicrobial, antioxidant, and anti-inflammatory properties [13–15]. Ginger has bioactive molecules like gingerol and shogaol, garlic contains organosulfur compounds like allicin and diallyl disulfide, and

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 8 (2025)

Online ISSN
Print ISSN
3007-3189

http://amresearchreview.com/index.php/Journal/about

kalonji yields thymoquinone and a variety of polyphenol molecules [16]. These molecules are not only effective reducing and capping agents for the formation of nanoparticles but also are involved in achieving better bioavailability and biomedical activity of the AgNPs [17]. Though single-plant extracts have been used for green syntheses, synergy between the three plants for AgNP preparation is yet to be explored in full. This report bridges the gap by utilizing a tri-herbal phytochemical apparatus for the preparation of AgNPs, expecting the combinatorial strategy to yield nanoparticles with better physicochemical stability and increased antimicrobial activity [18,19]. In fact, our report anticipates that the AgNPs obtained from the common extracts of ginger, garlic, and kalonji will show dose-dependent antibacterial activity, with appreciably increased inhibition zones towards the MDR strains in relation to the AgNPs obtained from single-plant setups.

To prove this hypothesis, aqueous extracts of the chosen botanicals were employed for the synthesis of silver nanoparticles. Physicochemical investigations were carried out extensively with Fourier-transform infrared spectroscopy (FTIR) for functional group analysis, scanning electron microscopy in association with energy-dispersive X-ray spectroscopy (SEM-EDX) for morphology and elemental analysis, dynamic light scattering (DLS) for particle size, and zeta potential for determination of colloidal stability and surface charge. Antimicrobial activity of the prepared AgNPs was assessed for their effect on four clinically important multi-drug-resistant (MDR) bacteria, *E. coli*, *P. aeruginosa*, *S. aureus*, and *A. baumannii*, utilizing the agar well diffusion model with varying concentrations of the nanoparticles for the analysis of strain-specific and dose-dependent responses.

Above and beyond the demonstration of basic antimicrobial performance, this study seeks to drive the advancement of scalable, biocompatible, and environmentally friendly plant-derived nanotherapeutics. These findings have potential for translation into the formulation of antimicrobial coatings, wound dressings, and disinfectant systems in regions of greatest resource limitation and corresponding AMR burden. By converging green nanotechnology and phytotherapy, this study joins a mounting collection of evidence in favor of eco-sustainable approaches addressing the problem of AMR in the post-antibiotic period.

Materials and Methods

Fresh ginger rhizomes of *Zingiber officinale*, *Allium sativum* bulbs, and *Nigella sativa* seeds were obtained from certified organic shops in Lahore, Pakistan. Analytical reagent grade silver nitrate ($AgNO_3$, >99% pure) was bought from Sigma-Aldrich (USA). Clinical isolates of *Escherichia coli*, *Staphylococcus epidermidis*, *Pseudomonas aeruginosa*, and *Acinetobacter baumannii* were provided by the Microbiology Culture Collection, from previous studies.

Preparation of Plant Extracts

Each 10 g of plant material was washed over running tap water, washed with sterile distilled water, and processed in aseptic conditions. Black cumin seeds were whole, and ginger and garlic were chopped after peeling. Each sample was homogenized in 100 mL sterile distilled water in a sterile mortar and pestle. Whatman No. 1 filter paper was used for the filtration of the homogenates in order to eliminate coarse

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 8 (2025)

Online ISSN
Print ISSN
3007-3189

http://amresearchreview.com/index.php/Journal/about

residues. Filtrates were stored at 4 °C and were used within 24 hours for maximal phytochemical activity.

Green Synthesis of Silver Nanoparticles

Silver nanoparticles were prepared by adding 10 mL of the freshly prepared plant extract into 90 mL of 1 mM aqueous $AgNO_3$ in sterile 250 mL Erlenmeyer flasks. Reaction mixtures were placed in the dark at ambient temperature (25 ± 2 °C) for 24 hours for the reduction of the metal ions. Visual confirmation of the formation of AgNPs was noted with a progressive color change from pale yellow towards brown color. Confirmation of the synthesis of the nanoparticles was also carried out with UV–Visible spectrophotometry (Shimadzu UV-1800), with absorbance recorded in the range 300–700 nm. Surface plasmon resonance (SPR) characteristic peak, between 420–450 nm, was a confirmation of the formation of the AgNPs.

Purification of Silver Nanoparticles

The synthesized nanoparticles were centrifuged at 12,000 rpm for 15 minutes at room temperature and the supernatant was removed, and the pellet was washed thrice with sterile distilled water in order to eliminate remaining phytochemicals and excess silver ions [20]. Each wash was followed by centrifugation under the same conditions. The final pellet obtained after purification was dried for 12 hours at 60 °C and stored in tightly closed containers for further analysis.

Characterization of Nanoparticles

The AgNPs synthesized were characterized by a set of analytical methods:

- **UV–Visible Spectroscopy** was employed for monitoring the optical properties and validating nanoparticle formation by SPR.
- **Dynamic Light Scattering (DLS)** and **zeta potential analysis** were carried out by a Malvern Zetasizer Nano ZS for measuring hydrodynamic size and surface charge stability, respectively.
- **Fourier Transform Infrared (FTIR) Spectroscopy** (Shimadzu IRTracer-100) was used for determining the functional groups involved in phytochemical-mediated reduction and capping.
- **Scanning Electron Microscopy (SEM)** (JEOL JSM-6490LV) was utilized to examine particle morphology, while **Energy Dispersive X-ray Spectroscopy (EDX)** confirmed elemental composition, including the presence of silver and co-associated elements such as oxygen, phosphorus, and chlorine.

Evaluation of Antimicrobial Activity

The antimicrobial activity of the green-synthesized AgNPs was determined through the Kirby-Bauer disc diffusion test. Mueller-Hinton agar (MHA) was seeded with bacterial suspensions with 0.5 McFarland turbidity [21]. Filter paper sterile discs with a diameter of 6 mm were soaked with 20 µL of suspensions of AgNPs at 50, 100, and 200 µg/mL concentrations. Gently, the discs were positioned on the surface of the seeded MHA plates and incubated at 37 °C for 24 hours. Zones of inhibition were measured in millimeter units with a digital caliper. Gentamicin and ciprofloxacin discs were used as positive antibiotic controls, and sterile distilled water was used as a

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 8 (2025)

Online ISSN
Print ISSN
3007-3189

http://amresearchreview.com/index.php/Journal/about

negative control.

Statistical Analysis

All experiments were carried out in triplicates, and the values were represented as mean ± standard deviation (SD). Statistical analysis between the treatment groups was carried out by one-way analysis of variance (ANOVA), with Tukey's post hoc test used for comparison between the groups. GraphPad Prism 9.0 (GraphPad Software, USA) was used for the analysis of the data. $P < 0.05$ was taken as statistically significant [22].

Results

Synthesis and Purification of Silver Nanoparticles

Silver nanoparticles (AgNPs) were synthesized successfully with aqueous extracts of *Zingiber officinale* (ginger), *Allium sativum* (garlic), and *Nigella sativa* (kalonji). An apparent color change from pale yellow to dark brown indicated the reduction of Ag^+ ions and confirmed nanoparticle formation, attributable to the surface plasmon resonance (SPR) phenomenon characteristic of silver nanoparticles. Post-synthesis, centrifugation effectively removed residual precursors, yielding purified AgNPs, as evidenced by the appearance of distinct pellets at the bottom of the reaction tubes.

Characterization of Synthesized AgNPs

Dynamic Light Scattering (DLS) and Zeta Sizer Analysis

The green-synthesized AgNPs exhibited a broad size distribution, with a mean hydrodynamic diameter of 1044.7 nm, confirming a polydisperse nature. Three distinct peaks were detected: the majority of particles clustered around 179.72 nm (54.72%), followed by larger particles at 2562 nm (44.27%) and a smaller fraction at 11,512 nm (1.01%). The polydispersity index (PDI) was 25.7%, indicative of moderate heterogeneity in particle sizes (Table 1).

***Table 1**. Zeta Sizer Analysis of Green Synthesized AgNPs*

Parameter	Value	Description
Hydrodynamic Diameter	1044.7 nm	Average particle size in suspension
Polydispersity Index (PDI)	25.7%	Measure of particle size distribution heterogeneity
Diffusion Coefficient	0.5 µm²/s	Particle diffusion rate in medium
Transmittance	1.4%	Optical transparency of colloid
Baseline	1.023	Instrument signal baseline
Mean Intensity	276.3 kcounts/s	Mean light scattering intensity
Absolute Intensity	1,624,404.6 kcounts/s	Total detected light scattering

Zeta Potential Analysis

Zeta potential analysis recorded a value of –35.4 mV, reflecting strong electrostatic repulsion among nanoparticles and thus high colloidal stability. This negative charge

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 8 (2025)

Online ISSN
Print ISSN
3007-3189

http://amresearchreview.com/index.php/Journal/about

is attributed to phytochemical compounds that coat the nanoparticle surfaces, acting both as reducing and stabilizing agents.

FTIR Spectroscopy

FTIR spectra (figure 1) exhibited prominent peaks corresponding to functional groups such as O–H (hydroxyl), C=O (carbonyl), and C–C stretching vibrations. These signals suggest the active participation of phenolic, flavonoid, and terpenoid compounds in both the reduction and stabilization of AgNPs.

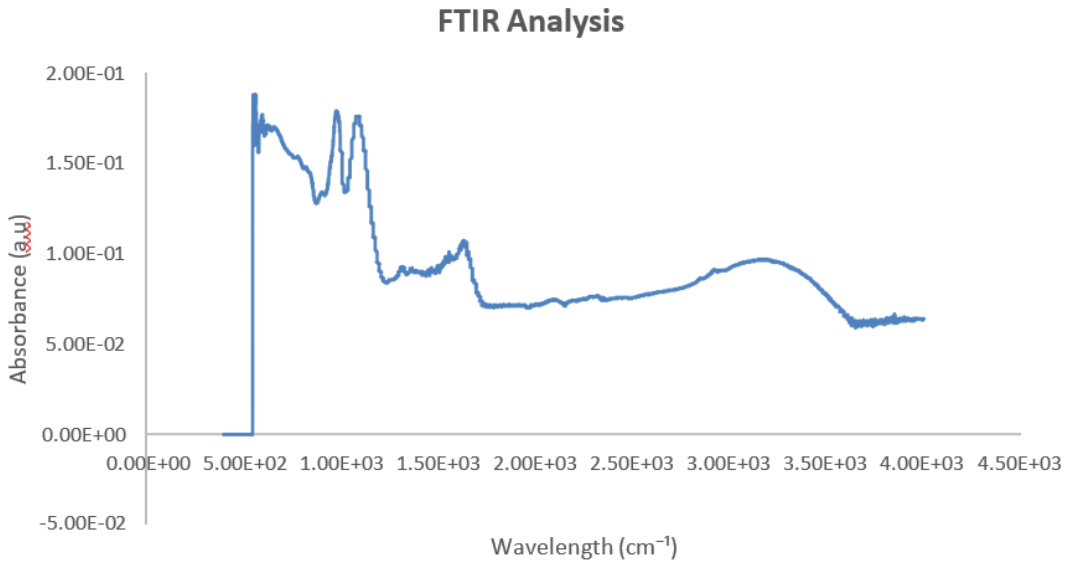

Figure 1: FTIR analysis of AgNPs

SEM and EDX Analysis

SEM micrographs revealed that the particles were predominantly spherical and polydisperse in nature. Irregular shapes were observed in both low- and high-magnification images. EDX spectral analysis confirmed the elemental presence of silver (39.2% by weight), alongside associated elements such as oxygen, carbon, phosphorus, chlorine, magnesium, and calcium—evidence of organic capping with biomolecules.

Antimicrobial Activity of AgNPs

Against *Pseudomonas aeruginosa*

AgNPs displayed a concentration-dependent antimicrobial effect. The zone of inhibition (ZOI) increased from 5.2 mm at 0.005 g to 15 mm at 0.05 g, indicating enhanced antibacterial efficacy at higher concentrations (figure 2).

Against *Acinetobacter baumannii*

No inhibition zones were observed at any of the tested concentrations, suggesting resistance or insensitivity of *A. baumannii* to the synthesized AgNPs under the

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 8 (2025)

Online ISSN
Print ISSN
3007-3189

http://amresearchreview.com/index.php/Journal/about

experimental conditions (figure 2).

Against *Staphylococcus epidermidis*

The ZOI initially increased at lower concentrations (5.2 mm at 0.005 g and 7.8 mm at 0.01 g) but showed a notable decrease at higher concentrations (4.5 mm at 0.02 g and 3.8 mm at 0.05 g). This non-linear pattern may indicate bacterial adaptation or the effect of nanoparticle aggregation on antibacterial efficacy (figure 2).

Against *Escherichia coli*

A marked increase in ZOI was recorded at 0.01 g (12.5 mm), followed by a reduction at higher concentrations (6.7 mm at 0.02 g and 5.4 mm at 0.05 g), suggesting that optimal antimicrobial activity was achieved at an intermediate dosage (figure 2).

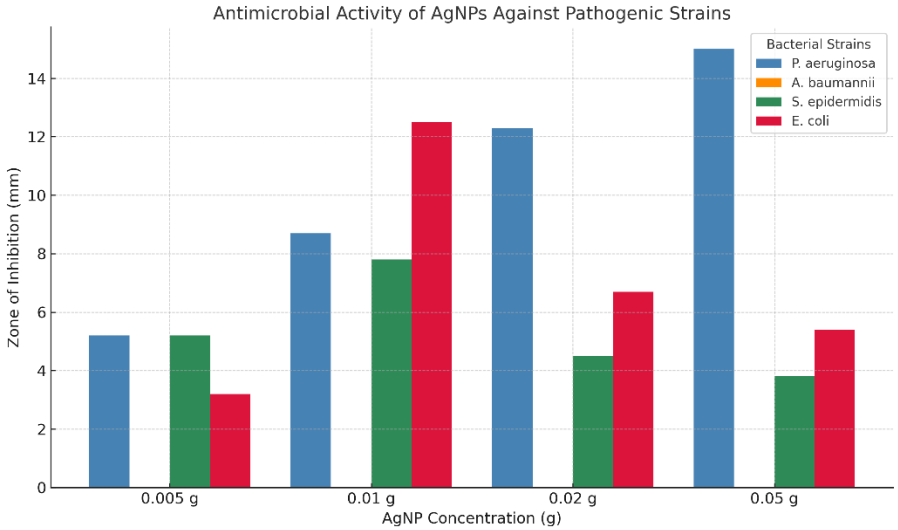

Figure 5: ZOI of Inhibition of all strains

Discussion

Our study points out that a green method can be used to form silver nanoparticles (AgNPs) with aqueous extracts of Allium sativum (garlic), Zingiber officinale (ginger) and Nigella sativa (black cumin). Given that worldwide attention is now on ecologically responsible nanomaterial synthesis, this is a particularly valuable approach. The distinctive color of brown, linked to AgNPs made using SPR techniques, showed up when I measured the absorption peaks which fell within the 420–450 nm range on my UV–Visible setup. This observation agrees with the recent work done by Rajak et al. (2023) and Ödemiş et al. (2022), testing Curcuma longa and Salvia officinalis, respectively which proves the formation of nanoscale silver [23,24].

Approximately 80% of the nanosuspension particles had mean hydrodynamic diameters of more than 1000 nm, suggesting some aggregation caused by the rich phytochemicals from both plant extracts. What was seen here also matches the observations of Aremu et al. 2022 [25], who reported a similar distribution of particle sizes for Azadirachta indica extract.

A mean potential of –17.9 mV was found by zeta potential analysis, suggesting that

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 3, Issue 8 (2025)

Online ISSN
Print ISSN
3007-3189

http://amresearchreview.com/index.php/Journal/about

the sample is moderately stable. Although 30 mV is usually considered as the threshold for electrostatic stability, our results are in close agreement with 16 to –22 mV [26]. Electrophoretic mobility and conductivity values prove that a colloidal system is stable.

The presence of terpenoids, proteins, and phenolic compounds as key reductive and stabilizing agents was identified through Fourier Transform Infrared (FTIR) spectroscopy. Comparable spectral peaks have been reported in AgNPs synthesized using Camellia sinensis (Sharma et al., 2022) [27], underlining the dominance of these biomolecules in the phytochemical synthesis of the nanoparticles. These constituents render the nanoparticles active antioxidants and antimicrobials, propelling the advances in biomedical applications.

Confirmation of spherical shape of nanoparticles formed was given by Scanning Electron Microscopy (SEM), while Energy Dispersive X-ray (EDX) analysis corroborated their chemical composition to be silver with minimal carbon and oxygen. These elements and morphology have also been reported by Gomathi et al. (2023) using Punica granatum extract [28]. The organic emission adds to the argument for bio-capping concerning the stability and bio-functionality of the particles.

We assessed the antimicrobial activity of synthesized AgNPs on clinically important pathogens such as Escherichia coli, Staphylococcus epidermidis Pseudomonas aeruginosa, and Acinetobacter baumannii. Inhibition was dependent on concentration, where P. aeruginosa and E. coli exhibited the greatest sensitivity. This is consistent with the work from Sajjad et al. (2025) and Hasoon et al. (2024) who observed the same trends with AgNPs derived from Withania somnifera and Tangerine fruit peel[29,30]. Also very interesting was how A. baumannii remained completely unresponsive to treatment, a trend observed in McNeilly et al. (2021) perhaps due to the organism's potent efflux pumps and inflexible membranes[31] .
The zone of inhibition values in our work were in agreement with Sriranjani et al. (2022) who reported 14-24 mm inhibition using AgNPs derived from Clerodendrum phlomidis [32]. It is important to highlight that the multiextract synthesis from this study produced inhibition zones as high as 23 mm which may indicate that the combined phytochemicals are more potentiated for antimicrobial action. Moreover, the use of three plants rich in phytochemicals distinguishes this study from others that used a single source, thus making it novel.

To sum up, this research contributes to the discipline of green nanotechnology by innovatively exhibiting an environmentally friendly biological process for AgNP synthesis. The extracts from A. sativum, Z. officinale, and N. sativa yield nanoparticles that possess considerable antimicrobial activity, good biocompatibility, and decent stability as colloids. Further research needs to include cell cytotoxicity tests, combined antimicrobial evaluation with standard antibiotics, and living organism testing. These results support the development of multi-herbal nanoparticle formulations for clinical applications.

Online ISSN
Print ISSN
3007-3189
http://amresearchreview.com/index.php/Journal/about

Conclusion

This work successfully highlights the first-time green synthesis of silver nanoparticles (AgNPs) using the aqueous extract of Allium sativum, Zingiber officinale, and Nigella sativa which offers an eco-friendly solution compared to the chemical and physical methods of synthesis. The synthesised AgNPs showed stable colloidal properties, various morphologies, and high antimicrobial activity, especially towards Escherichia coli and Pseudomonas aeruginosa. The antimicrobial activity stems from a combination of phytochemicals present in all three medicinal plants that may have further enhanced the reduction, capping, and biological activity of the nanoparticles. This method with tri-extracts showed higher than or comparable antibacterial efficacy and stability of the nanoparticles counter to the recent literature using singular extracts. Biogenically synthesized nanoparticles of silver proved to be useful in treating multidrug-resistant infections. Further studies are needed to elucidate in vivo toxicity, mechanism, and combination with standard antibiotics to optimize their use clinically. The technology described demonstrates a marked improvement towards the environmentally friendly and highly sustainable nanotechnology-based biomedicine.

Reference

[1] T.M. Coque, R. Cantón, A.E. Pérez-Cobas, M.D. Fernández-de-Bobadilla, F. Baquero, Antimicrobial Resistance in the Global Health Network: Known Unknowns and Challenges for Efficient Responses in the 21st Century, Microorganisms 11 (2023) 1050. https://doi.org/10.3390/microorganisms11041050.

[2] E.K. Oladipo, S.F. Adeyemo, G.J. Oluwasanya, E.O. Adaramola, S.B. Akintola, V.O. Afolabi, J.D. Ajagbe, O.H. Ojo, E.P. Kolapo, E. Owoeye, E.M. Jimah, A.O. Ayeleso, H. Onyeaka, Novel antibacterial agents and emerging therapies in the fight against multidrug-resistant *Acinetobacter baumannii*, Microbial Pathogenesis 200 (2025) 107361. https://doi.org/10.1016/j.micpath.2025.107361.

[3] A.A. Abebe, A.G. and Birhanu, Methicillin Resistant Staphylococcus aureus: Molecular Mechanisms Underlying Drug Resistance Development and Novel Strategies to Combat, Infection and Drug Resistance 16 (2023) 7641–7662. https://doi.org/10.2147/IDR.S428103.

[4] J. Teng, S. Imani, A. Zhou, Y. Zhao, L. Du, S. Deng, J. Li, Q. Wang, Combatting resistance: Understanding multi-drug resistant pathogens in intensive care units, Biomedicine & Pharmacotherapy 167 (2023) 115564. https://doi.org/10.1016/j.biopha.2023.115564.

[5] K.W.K. Tang, B.C. Millar, J.E. Moore, Antimicrobial Resistance (AMR), Br J Biomed Sci 80 (2023) 11387. https://doi.org/10.3389/bjbs.2023.11387.

[6] M. Thambirajoo, M. Maarof, Y. Lokanathan, H. Katas, N.F. Ghazalli, Y. Tabata, M.B. Fauzi, Potential of Nanoparticles Integrated with Antibacterial Properties in Preventing Biofilm and Antibiotic Resistance, Antibiotics 10 (2021). https://doi.org/10.3390/antibiotics10111338.

[7] H.D. Beyene, A.A. Werkneh, H.K. Bezabh, T.G. Ambaye, Synthesis paradigm and applications of silver nanoparticles (AgNPs), a review, Sustainable Materials and Technologies 13 (2017) 18–23. https://doi.org/10.1016/j.susmat.2017.08.001.

Online ISSN
Print ISSN
3007-3189
http://amresearchreview.com/index.php/Journal/about

[8] T.C. Dakal, A. Kumar, R.S. Majumdar, V. Yadav, Mechanistic Basis of Antimicrobial Actions of Silver Nanoparticles, Front. Microbiol. 7 (2016). https://doi.org/10.3389/fmicb.2016.01831.

[9] B. Ahmed, A. Hashmi, M.S. Khan, J. Musarrat, ROS mediated destruction of cell membrane, growth and biofilms of human bacterial pathogens by stable metallic AgNPs functionalized from bell pepper extract and quercetin, Advanced Powder Technology 29 (2018) 1601–1616. https://doi.org/10.1016/j.apt.2018.03.025.

[10] H. Duman, F. Eker, E. Akdaşçi, A.M. Witkowska, M. Bechelany, S. Karav, Silver Nanoparticles: A Comprehensive Review of Synthesis Methods and Chemical and Physical Properties, Nanomaterials 14 (2024) 1527. https://doi.org/10.3390/nano14181527.

[11] S. Rajkhowa, S.Z. Hussain, M. Agarwal, A. Zaheen, S.A. Al-Hussain, M.E.A. Zaki, Advancing Antibiotic-Resistant Microbe Combat: Nanocarrier-Based Systems in Combination Therapy Targeting Quorum Sensing, Pharmaceutics 16 (2024) 1160. https://doi.org/10.3390/pharmaceutics16091160.

[12] R. Mukherjee, C.-M. Chang, R.P. Pandey, S. Hameed, Role of Nanomedicine in Overcoming Antimicrobial Resistance: Challenges and Opportunities, in: M.Y. Wani, I.A. Wani, A. Rai (Eds.), Nanotechnology Based Strategies for Combating Antimicrobial Resistance, Springer Nature, Singapore, 2024: pp. 45–60. https://doi.org/10.1007/978-981-97-2023-1_2.

[13] Comparative Study of the Antimicrobial Activity and Phytochemical Properties of Allium sativum (Garlic) and Zingiber officinale (Ginger) Extracts on Some Clinical Isolates - ProQuest, (n.d.). https://www.proquest.com/openview/4f4743afa17d4357759f8e60cf582d20/1?pq-origsite=gscholar&cbl=2026366&diss=y (accessed May 30, 2025).

[14] A.K. Parade, D.K. Deokar, S.B. Adangale, D.K. Kambale, P.B. Meshram, Effect of addition of ginger (Zingiber officinale), and black cumin (Nigella sativa L.) on growth performance of white leghorn layer, Pharma Innovation 12 (2023) 2584–2587.

[15] R.S. Almasri, A.S. Bedir, S.M. Al Raish, Comprehensive Ethnopharmacological Analysis of Medicinal Plants in the UAE: Lawsonia inermis, Nigella sativa, Ziziphus spina-christi, Allium cepa, Allium sativum, Cymbopogon schoenanthus, Matricaria aurea, Phoenix dactylifera, Portulaca oleracea, Reichardia tingitana, Salvadora persica, Solanum lycopersicum, Trigonella foenum-graecum, Withania somnifera, and Ziziphus lotus, Nutrients 17 (2025) 411. https://doi.org/10.3390/nu17030411.

[16] C.O. Ajanaku, O.T. Ademosun, P.O. Atohengbe, S.O. Ajayi, Y.D. Obafemi, O.A. Owolabi, P.A. Akinduti, K.O. Ajanaku, Functional bioactive compounds in ginger, turmeric, and garlic, Front. Nutr. 9 (2022). https://doi.org/10.3389/fnut.2022.1012023.

[17] S. Simon, N.R.S. Sibuyi, A.O. Fadaka, S. Meyer, J. Josephs, M.O. Onani, M. Meyer, A.M. Madiehe, Biomedical Applications of Plant Extract-Synthesized Silver Nanoparticles, Biomedicines 10 (2022) 2792. https://doi.org/10.3390/biomedicines10112792.

[18] R. Islam, L. Sun, L. Zhang, Biomedical Applications of Chinese Herb-

Online ISSN
Print ISSN
3007-3189
http://amresearchreview.com/index.php/Journal/about

Synthesized Silver Nanoparticles by Phytonanotechnology, Nanomaterials 11 (2021). https://doi.org/10.3390/nano11102757.

[19] S. Wei, Y. Wang, Z. Tang, H.-B. Xu, Z. Wang, T. Yang, T. Zou, A novel green synthesis of silver nanoparticles by the residues of Chinese herbal medicine and their biological activities, RSC Advances 11 (2021) 1411–1419. https://doi.org/10.1039/d0ra08287b.

[20] S.F. Tehrani, A.G. Ac, M.A.M. Tuyaga, T.R. García, X. Banquy, V. Roullin, Critical assessment of purification processes for the robust production of polymeric nanomedicine., International Journal of Pharmaceutics (2024). https://doi.org/10.1016/j.ijpharm.2024.124975.

[21] M. Danaei, M.M. Motaghi, M. Naghmachi, F. Amirmahani, R. Moravej, Green synthesis of silver nanoparticles (AgNPs) by filamentous algae extract: comprehensive evaluation of antimicrobial and anti-biofilm effects against nosocomial pathogens, Biologia 76 (2021) 3057–3069. https://doi.org/10.1007/s11756-021-00808-8.

[22] T. Belayneh, S. Gebremichael, A.V. Chinchkar, T. Berhanu, A. Singh, A. Upadhyay, Comparative Study on Chemical Composition and Antioxidant Properties (GraphPad Prism Approach) of Wild Ethiopian Z. spina-christi and Indian Z. jujube Fruit Species, Food Anal. Methods 15 (2022) 2224–2237. https://doi.org/10.1007/s12161-022-02274-7.

[23] K.K. Rajak, P. Pahilani, H. Patel, B. Kikani, R. Desai, H. Kumar, Green synthesis of silver nanoparticles using Curcuma longa flower extract and antibacterial activity, (2023). https://doi.org/10.48550/arXiv.2304.04777.

[24] Ö. Ödemiş, S. Özdemir, S. Gonca, A. Arslantaş, M. Ağırtaş, The study on biological activities of silver nanoparticles produced via green synthesis method using Salvia officinalis and Thymus vulgaris, Turkish Journal of Chemistry 46 (2022) 1417–1428. https://doi.org/10.55730/1300-0527.3448.

[25] H.K. Aremu, L.A. Azeez, I.A. Adekale, H.K. Busari, Z.A. Aremu-Adebayo, A. Disu, H. Usman, O. Adeyemo, O. Oyewole, Green Synthesis of Silver Nanoparticles Using Azadirachta Indica and Their Biotoxicity Against Larvae of Culex Quinquefasciatus, (2022). https://doi.org/10.2139/ssrn.4238690.

[26] P. Bélteky, Rónavári ,Andrea, Zakupszky ,Dalma, Boka ,Eszter, Igaz ,Nóra, Szerencsés ,Bettina, Pfeiffer ,Ilona, Vágvölgyi ,Csaba, Kiricsi ,Mónika, Z. and Kónya, Are Smaller Nanoparticles Always Better? Understanding the Biological Effect of Size-Dependent Silver Nanoparticle Aggregation Under Biorelevant Conditions, International Journal of Nanomedicine 16 (2021) 3021–3040. https://doi.org/10.2147/IJN.S304138.

[27] R. Sharma, Rana ,Ajay, S. and Kumar, Phytochemical investigation and bioactivity studies of flowers obtained from different cultivars of Camellia sinensis plant, Natural Product Research 36 (2022) 2166–2170. https://doi.org/10.1080/14786419.2020.1844696.

[28] A. Gomathi, M.R. Kuppusamy, K. Aruna, T.M. Sridhar, Preparation of metal doped nanoparticles using flower extract of *Piper betle* and its anti-bacterial investigations, Materials Today: Proceedings (2023). https://doi.org/10.1016/j.matpr.2023.02.113.

[29] W. Sajjad, F. Ullah, R. Ullah, Z. Ullah, M. Ahmad, J. Zahir, S.U. Rahman, K.

Online ISSN
Print ISSN
3007-3189

Ullah, Q.S.U. Haq, Y. Aziz, J. Khan, Sania, Evaluating the Antibacterial Efficacy of Withania somnifera (Ashwagandha) against Various Bacterial Strains, Indus Journal of Bioscience Research 3 (2025) 17–23. https://doi.org/10.70749/ijbr.v3i4.954.

[30] B.A.A. hamza Hasoon, B.S. Mahmood, E.A. Mohamed, M.S. Jabir, K.H. Jawad, N.N. Hussein, G.M. Sulaiman, Y.H. Dewir, N. Mendler-Drienyovszki, Tangerine fruit peel extract mediated biogenic synthesized silver nanoparticles and their potential antimicrobial, antioxidant, and cytotoxic assessments, Green Processing and Synthesis 13 (2024). https://doi.org/10.1515/gps-2024-0126.

[31] O. McNeilly, R. Mann, M. Hamidian, C. Gunawan, Emerging Concern for Silver Nanoparticle Resistance in Acinetobacter baumannii and Other Bacteria, Front. Microbiol. 12 (2021). https://doi.org/10.3389/fmicb.2021.652863.

[32] R. Sriranjani, B. Srinithya, V. Vellingiri, P. Brindha, S.P. Anthony, A. Sivasubramanian, M.S. Muthuraman, Silver nanoparticle synthesis using *Clerodendrum phlomidis* leaf extract and preliminary investigation of its antioxidant and anticancer activities, Journal of Molecular Liquids 220 (2016) 926–930. https://doi.org/10.1016/j.molliq.2016.05.042.